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AVAILABILITY AND ACCESSIBILITY FOR OFFSHORE OPERATIONS IN THE MEDITERRANEAN SEA

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ABSTRACT

The study uses a 35 year dataset which can be used to provide a long-term assessment for assessing wave power resource, availability for wave energy converters, and multi-thresholds accessibility suitable for numerous vessels and important for offshore maintenance operations. The dataset demonstrates that winter months have harsher environmental conditions for the Western regions such as the Spanish coastlines, the Eastern regions such as the Aegean Sea record slightly higher waves during summer months. The dataset also identifies the seasons with lower resources which have higher accessibility which will have higher accessibility and benefits offshore to construction and maintenance operations of offshore energy activities.

It has been shown that the availability for wave energy depends on the operational range of a particular type of wave energy converter, hence threshold selection affects the availability distribution more than accessibility. Availability varies per region with Southern Aegean, Southern Italian and North African coasts having higher monthly values. Accessibility in nearshore areas is constantly over 90% with deeper waters presenting reduced levels. Statistical analysis carried out for this work shows predictable availability due to lower maxima, hence potentially enhancing wave energy converters operation; this however will depend on device properties. Furthermore, the resource analysis indicates that the dominant metocean conditions yield low wave height range.

Keywords: Wave Resource, Availability, Accessibility; Statistics

INTRODUCTION

Operations in offshore environments are a vital consideration for many industries for the pre (construction etc.) and/or post phases (maintenance, decommission, etc.). Recent years have seen a spur for consideration and development of offshore platforms and energy applications, such as offshore wind, and wave converters.

Based on the activity in question, data requirements may vary from very long-term historical (hindcast) data to short term forecasts. Most of the time long-term datasets are required for planning operations, with significant wave height (H_{m0}) being amongst the most important parameters. Datasets can be obtained by numerous methods such as buoys measurements, satellites, numerical wave models, and/or derivation by empirical formulations, though every option has its benefits and limitations.

In the Mediterranean Sea there is an extensive buoy network operated by various regional and national organisations, though access is not always under public domain. A limitation of using buoys as means to characterise the wave environment is in their spatial distribution and temporal recordings. Buoys are usually deployed at near coastal waters with measured resource affected by the surrounding environmental characteristics (coastlines, bottom depth) (Cavaleri and Sclavo 2006a). Their spatial distribution can not be used to generalise wave conditions for a larger area. Disparity of deployments underlines the fact that certain locations of interest for offshore activities may not have long-term coverage, not allowing robust operational and feasibility studies.

Satellites on the other hand offer high level of information but are limited by the fact that recordings have large gaps between each passing with some 10 or 30 days apart (pending on satellite mission). Additional limitation of satellites is that recording of wave parameters initiate ≈ 20 kilometers (km) off any coastline (Cavaleri and Sclavo 2006a; Cavaleri and Sclavo 2006b; Vinoth and Young 2011).

The use of empirical methods for derivation of waves while feasible does not ensure applicability over a large domain. Due to the complex nature of waves the spectrum considered for empirical derivation often does not account for wave-wave interactions.

Finally, numerical wave models offer an alternative when it comes to wave climate characterisation. They are based on wave theory principles, and are able to simulate sea conditions for a variety of spectrums. At the same time they account for computational demanding non-linear interactions and complex factors affecting wave generation and propagation, allowing for a realistic representation of the sea states over a large number of frequencies and large domains (Janssen 2008).

Concerning the wave climate in the Mediterranean Sea several studies have been conducted, but are focused on either very small areas of investigation (Barbariol et al. 2013; Catini et al. 2011; Guizien 2009; Liberti et al. 2013; Soukissian and Pospathopoulos 2006) or encompass a limited period of duration analysis (Soukissian et al. 2002; Vicinanza et al. 2007). Most long term studies associated with the Mediterranean Sea have introduced significant findings, predominately concerning wave climate investigations (Medatlas Group 2004; Ratsimandresy et al. 2008); and the most recent long-term studies in the region have delivered the long-term wave power resource of the Mediterranean (Lavidas et al. 2016; Besio et al. 2016).

Mentaschi et.al. (Mentaschi et al. 2015) parametrised the oceanic model Wavewatch III with a reference parametrisation scheme. The resulted model showed a good performance and was used by Besio et.al (Besio et al. 2016) to hindcast the wave power potential over 35 years for the Mediterranean Sea, with a focus on Italy. Lavidas et.al. (Lavidas et al. 2016) used the Simulating WAves Nearshore (SWAN), and parametrised the configuration of wind schemes with a high temporal wind dataset. The resulting 35 years hindcast used a nested approach and provided a coarse and several spatial higher resolution domains with fully non-linear components tuned, making the results suitable for nearshore areas.

Majority of studies in the past are based on oceanic models with spatial resolution hindering extrapolation of results to coastal areas as discussed in Ca$\tilde{n}$ellas et.al. (Cañellas et al. 2007). For a study to be useful in wave and power assessments, it must have at least 10 years of continuous data (Ingram et al. 2011) and use proper models or techniques suited for nearshore or deep waters. In Table 1 focus is given on dedicated Mediterranean studies that exceed the pre-described 10 years minimum duration. In addition, to these large scale studies, "smaller" domains focusing of specific regions in the Mediterranean, like the Balearic islands, the Aegean, Sicily, Italy (Monteforte et al. 2015; Emmanouil et al. 2016;

Jadidoleslam et al. 2016; Zacharioudaki et al. 2015; Ponce de León et al. 2016).

Evaluation of spatial distribution of mean resource, standard deviation, highest percentiles provide a long-term overview for the dominant metocean conditions. Although these are often not sufficient for offshore deployments and installations, with increasing interest in offshore applications there is a gap in knowledge on the accessibility that is vital for offshore activities over different significant wave heights (H_{m0}). Since most operations rely on vessels to carry out offshore works (Veritas 2011a; Katsouris and Savenije 2017), results from our analysis provide a look on how resource and regional characteristics affects accessibility.

Another issue addressed is the effect of H_{m0} on availability (i.e. operational time), for the increasing wave energy sector. Based on H_{m0} resource and operational operational wave energy converters (WECs) thresholds, availability is expected to change significantly especially for nearshore locations which are of interest for WECs. Wave power resource assessments are vital to identify regional "hot-spots", although this does not mean availability will be high if the resource is high, since the operational range of a WEC more responsible. Differences occur both in regional and temporal terms (season, monthly), indicating that the wave climate and surrounding characteristics favour specific regions for WECs application. Individual locations are taken from the nearshore high-resolution hindcast domains and provide a representative sample of varying depths and resource profiles. Variations, accessibility, availability, maximum values, and dominant sea states of the resource, have an important role in the preparation of any offshore activity and are fully analysed.

The following sections describe the data produced from the numerical model ans its use in determining the accessibility and availability of wave resources for different regions.

METHODOLOGY

The data presented here were produced from the SWAN model, a third generation numerical model specifically developed for nearshore and coastal waters. In the set-up consideration was given in calibrating all non-linear nearshore wave propagation physics, so that its application to coastal waters will have higher confidence. The dataset have been produced by simulating wave conditions in hindcast mode. The detailed calibration and validation of the model have been presented in previous works (Lavidas et al. 2016; Lavidas and Venugopal 2017). The model was based on a two way nested scheme, with spatial resolution for the Mediterranean domain of 0.1^o (degrees) and several nested domains that have a spatial resolution of 0.025^o (A-D), see Figure 1. Different wind scheme configurations were used to calibrate the model, the wind input used had a 1 hour temporal resolution with spatial resolution of 0.351^o latitude and longitude (Saha et al. 2010). The higher temporal resolution of the wind dataset helps to alleviate under-estimations, as they encountered in numerical wave modelling (Cavaleri 2009).

For offshore installations most important component for the operation of vessels is the magnitude of significant wave height (H_{m0}) (Veritas 2011a; Katsouris and Savenije 2017), followed by the range of wave peak periods (e.g., peak wave period T_{peak}, mean zero crossing T_{m02}) and wind speed (U_{wind}). This study investigates predominately the significant wave height H_{m0}, and its spatial distribution considered in this study.

RESULTS

Spatial resource distribution

As mentioned waves are generated predominately due to wind which also drives swells to travel across the basin. The "smaller" distances met in the

Mediterranean do not amplify swells as much, for example when compared to the Atlantic. This leads H_{m0} reaching the coastlines to have lower magnitude and T_{peak} having higher frequencies, indicating that the resource is comprised by short and frequent waves.

The mean H_{m0} resource shows that larger magnitude waves are encountered in Western Mediterranean, Spain has 0.8-1.2 meters (m), Southern Italy 1-1.2m, Ionian and Adriatic sea with 0.9-1m and 0.65-0.8m respectively (see Figure 2). In Southern Aegean H_{m0} magnitudes are 1-1.4m, 0.6-0.8m for the North, and 1-1.2m in the Central part. Libyan Sea is exposed to 0.8-1.2m on the West and East (neighbouring Egypt). Tunisia and Algeria share parts of the resource with Spain and Italy with 0.9-1.2m. Finally, at the Mediterranean South East near Cyprian coastlines waves reach up to 0.8m. In terms of wave periods the coastlines such as the South of France, Adriatic Sea and North Aegean, attain very low values of 3.5-5 seconds (sec) (high frequency waves). Southern parts of Tunisia have periods from 3-4 sec, while majority of Central Mediterranean from latitudes 34^o-40^o have values from 5-7 sec.

The mean resource provides us with an overview of the area, however it is not able to capture smaller variations i.e. monthly and seasonal. Thus, further exploration for the monthly metocean resource conditions is necessary. Most energetic months are during winter January-February-November-December, lowest magnitudes are during summer months (June-July-August).

In terms of H_{mo} monthly distribution deep water locations present the higher magnitudes, from January to February highest resources are met in the South-West parts of the Aegean, the coasts of North Africa (Libya and Egyptian coasts), and the region North-West of the Balearic Sea. The Adriatic and higher Ionian Seas, due to the orography (encapsulated) present the lowest resources. In the Mediterranean South East, resource diminishes after Cyprus due to "blockage" effects and small fetches after the island (see Figure 3, Figure 4 and Figure 5). From September to December highest waves are encountered in the same regions, with the central and South East Aegean having higher values for September-October, while in November the Balearic Sea and Algerian coastlines have the highest wave heights. In December the central part of the North African coast has high exposure but in spring and summer months (May-August) resource is lowered significantly. Majority of the distribution is located in the Western and lower Southern parts of the Mediterranean. In terms of lower levels, the Adriatic and North Aegean region are the lowest throughout annual and monthly distributions. Expanding on the wave resource analysis, standard deviation (STD) and the levels of highest percentiles offer insight to the variation and magnitudes expected (see Figure 6).

Highest deviations are found in the North East Balearic Sea perpendicular to the French coastlines. Lower resource areas such as the Adriatic have low level of variation. Interestingly, the central Aegean belt which has a good resource offers moderate levels of deviation, indicating lower variability. Southern and Eastern parts of the Mediterranean exhibit low standard deviation as well. In terms of T_{peak} large variations are seen at the Algerian coastlines, off the West Coast of Sardinia. In the Tyrrhenian Sea higher values are attained for the coasts spanning from Northern Sicily to Calabria. At East Mediterranean, the Southern Crete has the largest variation levels, similar to the ones found at Sardinia and at the Gulf of Grand Sirte (Gulf of Surt).

Monthly STD values show that specific regions have higher deviations, for autumn and summer months the North Balearic Sea, Central Aegean, Cote d'Azur and South Ionian have the largest deviation in H_{m0} from 1-1.8m. Spring and summer periods have lower wave resources and much lower deviations, with the exception of North East Balearic Sea. The lower Southern part of Italy has moderate to low STD levels for majority of months (see Figure 6), however the Southern and South East Mediterranean attain high values of STD during March-April-May.

The percentiles chosen present with majority of H_{m0} lower that the percentile value, differences between 99^{th} and 95^{th} percentiles are higher for Western regions of the Mediterranean ($\approx$ 1.5-2 m), while the Eastern part shows small differences between the two i.e. Central Aegean has $99^{th} \approx$ 3.5-4 m and $95^{th} \approx 1m$ (see Figure 7).

Accessibility

Most offshore installations require operation and maintenance (O&M), and potential additional infrastructure works. Operating in offshore environments is not always as straight forwards as inland regions. Thus, is of major importance to assess the time "slots" for which metocean conditions are suitable for deployments of crews and vessels (Katsouris and Savenije 2017).

Majority of O&M vessels are able to operate in a variety of sea-states depending on type of ship and wave conditions. Accessibility, is defined as the percentage of time for which the conditions met at a location are equal or less than a specific threshold. This ensures that deployed vessels, crews and offshore works are performed under safe conditions. Such thresholds are usually set from 1m-3m where majority of vessels are able to operate. In the subsequent presented analysis we have used an range of thresholds (t) from 1.5m up to 4m, incrementally increased by 0.5m. Results provide the percentage of time for which the region/location favours deployments for O&M and/or construction.

Majority of the time is suitable for offshore works at the Mediterranean offshore, especially when vessels requires $\leq$ 3 m. In the cases that thresholds are set to lower heights $\leq$ 1.5-2 m, then the percentage reduce, but still remains over

70% (see Figure 8). In contrast to exposed oceanic coasts which express higher accessibility depending on season (i.e. summer). In the Mediterranean higher levels of accessibility are due to the inherently lower resource. The monthly lower levels of H_{m0} allow for higher accessibility from spring to autumn months, while it reduces for winter months it does not drop in nearshore areas below 50% (see Figure 2 for the overall resource, for seasonal overview Figure 3, Figure 4 and Figure 5).

Availability

While accessibility is a characteristic that can be used by numerous offshore activities including platforms, and offshore wind farm maintenance operations. Availability mostly concerns wave energy converters (WEC), and the energy production from the resource. As in the case of wind turbines, WECs have a specific ranges of operation. Depending on their operative principles and deployment restriction, WECs can be classified according to depth as deep, intermediate, nearshore and shoreline devices. In terms, of resource utilisation, distinctions can also be made depending on their cut-in (H_{cut-in}), cut-off ($H_{cut-off}$) and nominal performance, classifying them as suitable for low and/or high resources.

Availability is the percentage of time for which the resource favours WEC operation, in this study availability is set according to H_{m0} that affect production and survivability. Like other renewable converters (i.e. wind) WECs have specific attributes concerning start of operation (H_{cut-in}) and end of operation (or survival mode) ($H_{sut-off}$). For wave energy applications resource availability has impact on the financial and technical performance (de Andres et al. 2015; Guanche et al. 2015).

From available literature (Babarit et al. 2012) and by cross-comparison of converters done by the authors favourable WEC for the Mediterranean region, should have a very low wave height cut-in operation and achieve its nominal capacity relatively quick (Lavidas and Venugopal 2017). Due to lower wave heights in the region, this means that this selected WEC will be optimally operated. Availability depends on two specific thresholds the cut-in and cut-off wave height taking into account the variety of WEC, limits are set with thresholds of H_{cut-in}=0.5m and $H_{cut-off}$=4m, WECs have different periods in their power matrix however H_{m0} is the only constant parameter, while different wave periods can be used.

As in the case of accessibility, availability also attains higher values due to milder wave resource, and limits ($H_{cut-in/off}$) which are set to a specific range and suggesting that WECs will have favourable operation. It has to be noted that availability of over 70% is achieved in deeper regions, however these cannot be considered operational depths for WECs for which deployment depths are limited to $\leq$ 150-250 m. Focus of the analysis is placed in coastal and intermediate depth regions, for this reason all availability analysis is limited to regions and depths for $\leq$ 250 m, depth considerations can be expanded with use of floating hybrid systems, however this is not in the current scope of the study.

Availability at the majority of coastline is within a range of 35-50%, indicating that WECs favour operation within the H_{m0} thresholds, will have moderate to high operation and energy production (see Figure 9). This though does not represent the capacity factor, it represents the percentage of time for which operational condition satisfy the thresholds of operation. While overall availability is satisfactory monthly assessment show the periods (months-seasons) which obtain higher levels of potential operation.

From October till February availability near the coastlines is $\geq$ 40% (see Figure 10 and Figure 12), with areas that were identified in the H_m0 assessment as energetic (see section 3) having higher percentages. More specifically the central and South East Aegean around the Cyclades, and Crete attain high values at coastal region over 60-70%, while the North Aegean has availability $\approx 30\%$ during winter months. Higher values are also recorded for the North African coastlines ranging from 50-60%. At the central part of the Mediterranean, specifically Italy (Straits of Messina, Sicily) and Tunisia have moderate levels of availability ranging from 30-50%. Finally, the Spanish, South French and Algerian coasts have similar values from 25%-45%.

Most interesting part in the availability analysis is the differentiation that regions attain throughout the months May-August (see Figure 11). Starting from May until availability levels for the central and Western part of the Mediterranean from 40-60% drop $\approx$ at half. On the other hand, Central Aegean, East Mediterranean (Levantine), and majority of South East Egyptian and Libyan coastlines retain higher values from 60-80%. In the central and South East Aegean there is an obvious concentration of "higher" availability shared with the Turkish coastlines. For the same period Algerian coastlines have lower percentages, with majority of areas from 20-40%. In enclosed areas such as the Adriatic Sea and the Northern part of the Aegean, the very low availability can be attributed to H_{cut-in} not satisfying the lower limit, while for the Eastern Spanish and South East Italian coasts the $H_{cut-off}$ is often exceeded.

Assessing the nearshore metocean conditions

In addition, to the large spatial domains several locations distributed around the Mediterranean coasts are extracted, by the higher resolution domains (A-D, see Figure 1), with recording interval of 30 minutes, and analysing the metocean characteristics over 35 years. Majority of offshore activities and constructions are situated at depths $\leq$ 500 m or $\leq$ 80 km, the extracted locations are distributed in varying depths (from 10 to 250 m) over the region to provide a holistc view of the region (see Figure 13).

The previous sections of accessibility and availability are complemented by the recordings of resource H_{m0} and percentiles. This allows for a multi-criteria selection depending on the type of usage for a site. Offshore constructions, and maintenance works require small H_{m0}, while wave energy application favour locations with higher resource. In section 3 levels of accessibility drop when thresholds are lowered, for higher thresholds (t_4 and above) the regions have high accessibility. As thresholds increase so does the positioning of clusters with higher (i.e. higher magnitude H_{m0}) increasing levels of accessibility (see Figure 14). This can be traced back to the lower resource, especially in the summer months that increases the percentage of accessible time.

Availability on the other hand is suitable for wave energy site characterisation, which combined with local climate studies can aid in WECs selection based on mutual dependence of power production and metocean conditions. Majority of locations show availability percentages within the range of 50-65%, with, lower operating devices are expected to more efficient in annual operation. In addition, low H_{m0} magnitudes in the Mediterranean can prove beneficial device survivability and also lower the cost of installation.

In Figure 15, the left graph (a) displays the monthly availability for the set ranges at low wave energy region. The location is sited at the Euboia island in the North West of the Aegean. From the resource assessment information, the location is not exposed to significant H_{m0} levels, in regards to the general overview of the central Aegean, as discussed in section 3. The location often fails to reach the H_{cut-in}. This is observed by the mean availability values throughout the years and months. Dominant availability levels indicate that exploitable resource will be only 40-45% of the year. On the other hand the same figure, displays on graph (b) another point in the Southern Aegean region. It is located at the energetic region West of Crete, which is exposed to higher values throughout the year. The availability of the location in this case is significantly higher, with a mean value $\approx 70-75\%$ per month. In this case the majority of non-utilised levels is due to exceedance of the $H_{cut-off}$ threshold. In Table 2 all values are summarised for extracted locations.

The magnitude of H_{m0} for all points is moderate to low, however in several instances maximum events exceed 5m. Average number of $\overline{H_{95^{th}}}$ and $\overline{H_{99^{th}}}$ suggests that the expected range does not exceed 3.05 m and 4.6 m respectively. Thus, in the case of WEC selection these operational conditions should be taken into account. A WEC with nominal operation at lower wave heights, will be ideal for the majority of the Mediterranean region. Availability, based on the set thresholds (minimum, maximum) presented in section 3, shows high levels for potential energy exploitation within the aforementioned limits. Accessibility levels at thresholds t_3-t_6 show that O&M and/or site approaches are feasible all year round. Although, taking into account that mean accessibility levels often exceed 75% even for a low threshold, it is logical to assume that O&M will not be hindered much by metocean conditions.

In the Central Aegean belt annual maxima are $\approx$ 3.5-4 m, in the Southern Aegean near Crete annual maxima are varied more, specifically the Crete2 location attains values as high as 6.8 meters in 2010, while the preceding year (2009) it maximum value was $\approx$ 4.5 m. Crete 1 reaches it highest value in 1991 $\approx$ 6.2 m, again with the preceding year maximum $H_{m0} \approx 3.1$ m. Athos, Euboia and Attika are Northern Aegean locations with lower mean H_{m0} resource, as they are positioned in areas with low depths and quite close to the coasts. Nevertheless, Athos has a mean value of 0.81 m, 0.24 m less than Crete2, although its maximum H_{m0} over the period exceeds that of Crete2 by $\approx \pm 0.2$ m, the lowest mean is affected by the non-exposure to higher swells that are found in Southern parts.

Locations at Southern Sicily and Gulf of Messina, have mean $H_{m0} \approx$ 1-1.3

m. Regions at Northern Sicily and lower Western Tyrrhenian Sea have annual means $\approx$ 0.75-1 m with similar variations, the areas present variations $\approx \pm$ 0.2 m in their mean values. In terms of annual maxima, levels show similar magnitude ranges regardless of region, H_{m0} annual maxima are over 4 m and can reach up to 8 m, this can also be observed in the higher values of percentiles and wave power resource (see Table 2).

At Southern France mean H_{m0} is between $0.5 - 1.1$ m, with annual variations ± 0.15 m,in annual maxima trends of occurrence and magnitudes are similar with small differences ± 0.75 m. However, annual maxima variations are found at higher,f or example while all locations attain a high value in 1982 $\approx >$ 5.6 m the following year maxima occurrence recorded is reduced by 2.1 m to $\approx$ 3.5 m, similar behaviour is repeated in 1997 and 2013. At Spanish locations maxima and annual deviations are volatile, and with some changes from year to year, annual H_{m0} deviation does not exceed ± 1 m (pending on location). All locations at Tunisia and Libya regions present similar trends, with very small annual location differences ± 0.25 m.

DISCUSSION

A high number of human activities and operation depend on local metocean conditions, and while the wave environment of the Mediterranean Sea is not as energetic as the oceanic coasts it requires evaluation for offshore activities. The study investigates various associated indices (resource, accessibility, availability) around the Mediterranean for a duration of 35 years, with data produced by a calibrated-validated nearshore numerical wave model.

Winter months have higher recordings of H_{m0} with annual magnitudes not presenting large deviations. Highest waves are encountered in the North West and Central part of the Mediterranean. In terms of monthly distribution, the

Central Aegean and North East African (Egyptian coast) present higher levels in summer months. During those months H_{m0} is reduced in the West, with variations being more notable for deeper and less "useful" waters. Nearshore regions present smaller variations and increased accessibility levels. Suggesting that offshore activities are well within the limits for the majority of vessels. Even with a low threshold accessibility exceeds 65% throughout, an important parameter for offshore activities, engineering construction and shipping (Veritas 2011b; Katsouris and Savenije 2017; Guanche et al. 2015).

Availability of production is high due to the lower resource present, favouring the operation of low resource WEC. Majority of locations indicate that the range of operation should be from 0.5 to 3 m H_{m0}, while wave periods should consider operation for high frequencies (low periods) in the span of 2-5 sec. While the resource potential available power is lower, reduced extremes conditions can benefit offshore installations, since maximum recorded wave heights are lower than the open Atlantic coasts. This can result in less capital expenditure during the construction phases. With higher accessibility levels also indicate potential lower costs for maintenance and operation processes.

Limited number of studies for availability, accessibility for the region exist, Guanche et.al. (Guanche et al. 2015) who performed a similar analysis based on the oceanic model with a spatial resolution of 1.5^o longitude and 1^o latitude (Reguero et al. 2012). Their study focused predominately on the Atlantic coast for wave energy and availability levels. Their overall values correspond with this study, indicating high availability levels $\geq$ 90%. It has to be noted that the threshold used in that study, was $H_{m0} \leq 5$ m. In contrast to oceanic models that have limitations to resolve nearshore environments due to the non-linear nearshore interactions not fully resolved.

Katsouris et.al. (Katsouris and Savenije 2017) assessed the accessibility of different vessels in the North Sea, for the potential maintenance and operation of offshore wind farms. In that study they indicate the different characteristics of vessels, alongside their maximum operative limits. The accessibility levels estimated varied according to the thresholds used. It also concluded that the accessibility for offshore platforms and based on the metocean conditions, has an impact on the cost of vessels hiring and potential the project finances.

CONCLUDING REMARKS

The focus of the study was on a detailed long-term resource assessment and site characterisation for the Mediterranean Sea. Since all offshore applications depend on the levels and magnitude of H_{m0}, evaluating the resource levels and distribution allows for a detail examination coastal areas. Following the quantification of resource levels, analysis based on annual and monthly data were undertaken, and estimates of availability and accessibility levels are presented.

Accessibility levels are derived based on H_{m0} and allowed to estimation of percentage of time at which specific locations will be accessible for different upper limits thresholds, in essence all sea states below a certain limit that will allow offshore installation works and maintenance. Depending on selected thresholds, the percentage of accessibility varied; and for values $\geq$ 2.5 m accessibility percentages are over 95% throughout the region. For thresholds below 2 and 1.5 m accessibility percentages differed from region to region. When low thresholds are considered accessibility levels were found to be high and exceeded 70%.

Availability, depends mostly on two thresholds a cut-in and cut-off H_{m0},this could be useful mostly to the wave energy sector. The availability data can be used to match the operation of candidate wave converters and predict their annual operational time. While this is not to be confused with the notion of capacity factor, it offers useful information that can be used to match converters suitable for the resource and achieve higher operational performance. This study showed that the opportunities for wave energy utilisation based on availability criteria, for the central Cyclades Islands at the Aegean, were found to be high ($\approx 75\%$). Nearshore locations with low resource did not satisfy the operational conditions (usually lower limit), and thus their availability for production was reduced to 20%. The monthly availability shows that lowest availability percentages were in line with low resource months, hence during late spring and summer months, regional availability decreased significantly which in turn will affect potential energy production.

The spatial variation of accessibility and availability reported in the paper for the wider Mediterranean region, will be of great use for the comprehensive description of metocean events.

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DISCLAIMER

The first author (George Lavidas) performed the analysis while a researcher at the Institute for Energy Systems, University of Edinburgh. George Lavidas produced the datasets and performed the analysis for accessibility, Atul Agarwal contributed in the analysis, Vengatesan Venugopal proof-read and commented the manuscript.

The authors declare no conflict of interest.

REFERENCES

Babarit, a., Hals, J., Muliawan, M., Kurniawan, A., Moan, T., and Krokstad, J. (2012). "Numerical benchmarking study of a selection of wave energy converters." *Renew. Energy*, 41, 44–63.

Barbariol, F., Benetazzo, A., Carniel, S., and Sclavo, M. (2013). “Improving the assessment of wave energy resources by means of coupled wave-ocean numerical modeling.” *Renew. Energy*, 60, 462–471.

Besio, G., Mentaschi, L., and Massino, A. (2016). “Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast.” *Energy*, 94, 50–63.

Cañellas, B., Orfila, A., Méndez, F., Menéndez, M., and Tintoré, J. (2007). “Application of a POT model to estimate the extreme significant wave height levels around the Balearic Sea (Western Mediterranean).” *J. Coast. Res. Spec. Issue*, 50(50), 329–333.

Catini, F., Montagna, F., Franco, L., Bellotti, G., Corsini, S., Inghilesi, R., and Orasi, A. (2011). “Development of a High-Resolution Nearshore Wave Forecasting/Hindcasting System for the Italian Coasts.” *Coast. Eng. Proc.*, 1(32), 1–14.

Cavaleri, L. (2009). “Wave Modeling-Missing the Peaks.” *J. Phys. Oceanogr.*, 39(11), 2757–2778.

Cavaleri, L. and Sclavo, M. (2006a). “A wind and wave atlas for the Mediterranean Sea.” *Eur. Sp. Agency, (Special Publ. ESA SP*, (614), 0–5.

Cavaleri, L. and Sclavo, M. (2006b). “The calibration of wind and wave model data in the Mediterranean Sea.” *Coast. Eng.*, 53(7), 613–627.

de Andres, a., Guanche, R., Vidal, C., and Losada, I. (2015). “Adaptability of a generic wave energy converter to different climate conditions.” *Renew. Energy*, 78, 322–333.

Emmanouil, G., Galanis, G., Kalogeri, C., Zodiatis, G., and Kallos, G. (2016). “10-year high resolution study of wind, sea waves and wave energy assessment in the Greek offshore areas.” *Renew. Energy*, 90, 399–419.

Guanche, R., De Andres, A., Losada, I. J., and Vidal, C. (2015). “A global analysis of the operation and maintenance role on the placing of wave energy farms." *Energy Convers. Manag.*, 106, 440–456.

Guizien, K. (2009). "Spatial variability of wave conditions in the gulf of lions (NW Mediterranean Sea)." *Vie Milieu*, 59(3-4), 261–270.

Ingram, D., Smith, G., Bittencourt-Ferreira, C., and Smith, H. (2011). *EquiMar: Protocols for the Equitable Assessment of Marine Energy Converters*. Number 213380.

Jadidoleslam, N., Özger, M., and Araliolu, N. (2016). "Wave power potential assessment of Aegean Sea with an integrated 15-year data." *Renew. Energy*, 86, 1045–1059.

Janssen, P. A. (2008). "Progress in ocean wave forecasting." *J. Comput. Phys.*, 227(7), 3572–3594.

Katsouris, G. and Savenije, L. (2017). "Offshore Wind Access 2017." *Report No. ECN-E-16-013*.

Lavidas, G. and Venugopal, V. (2017). "A 35 year high-resolution wave atlas for nearshore energy production and economics at the aegean sea." *Renewable Energy*, 103, 401 – 417.

Lavidas, G., Venugopal, V., and Agarwal, A. (2016). "Long-Term Evaluation of the Wave Climate and Energy Potential in the Mediterranean Sea." *4th IAHR Eur. Congr. 27th July - 29th July*, S. Erpicum, B. Dewals, P. Archambeau, and M. Pirotton, eds., Liege, Sustainable Hydraulics in the Era of Global Change, Advances in Water Engineering and Research, CRC Taylor and Francis,LLC, 247–253.

Liberti, L., Carillo, A., and Sannino, G. (2013). "Wave energy resource assessment in the Mediterranean, the Italian perspective." *Renew. Energy*, 50, 938–949.

Medatlas Group (2004). "Wind and Wave Atlas of the Mediterranean Sea." *Report No. April*, Western European Union.

Mentaschi, L., Besio, G., Cassola, F., and Mazzino, A. (2015). “Performance evaluation of Wavewatch III in the Mediterranean Sea.” *Ocean Model.*

Monteforte, M., Lo Re, C., and Ferreri, G. (2015). “Wave energy assessment in Sicily (Italy).” *Renew. Energy*, 78, 276–287.

Ponce de León, S., Orfila, A., and Simarro, G. (2016). “Wave energy in the Balearic Sea. Evolution from a 29 year spectral wave hindcast.” *Renew. Energy*, 85, 1192–1200.

Ratsimandresy, a. W., Sotillo, M. G., Carretero Albiach, J. C., Álvarez Fanjul, E., and Hajji, H. (2008). “A 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS Project.” *Coast. Eng.*, 55(11), 827–842.

Reguero, B. G., Menéndez, M., Méndez, F. J., Mínguez, R., and Losada, I. J. (2012). “A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards.” *Coast. Eng.*, 65, 38–55.

Saha, S., Moorthi, S., Pan, H. L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y. T., Chuang, H. Y., Juang, H. M. H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., Van Den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J. K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C. Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G., and Goldberg, M. (2010). “The NCEP climate forecast system reanalysis.” *Bull. Am. Meteorol. Soc.*, 91(8), 1015–1057.

Soukissian, T. and Pospathopoulos, A. (2006). “The Errors-in-Variables approach for the validation of the WAM wave model in the Aegean Sea.” *Sci. Mediterr. Mar.*, 7(1), 47–62.

Soukissian, T. H., Prospathopoulos, A. M., and Diamanti, C. (2002). "Wind and Wave Data Analysis for the Aegean Sea - Preliminary Results." *J. Atmos. Ocean Sci.*, 8(2-3), 163–189.

Veritas, D. N. (2011a). "Marine Operation General." *Report No. DNV-OS-H101*.

Veritas, D. N. (2011b). "MODELLING AND ANALYSIS OF MARINE OPERATIONS." *Report No. DNV-RP-H103*.

Vicinanza, D., Cappietti, L., and Contestabile, P. (2007). "Assessment of Wave Energy around Italy." *Power*, 256–262.

Vinoth, J. and Young, I. R. (2011). "Global Estimates of Extreme Wind Speed and Wave Height." *J. Clim.*, 24(6), 1647–1665.

Zacharioudaki, A., Korres, G., and Perivoliotis, L. (2015). "Wave climate of the Hellenic Seas obtained from a wave hindcast for the period 19602001." *Ocean Dyn.*, 65(6), 795–816.

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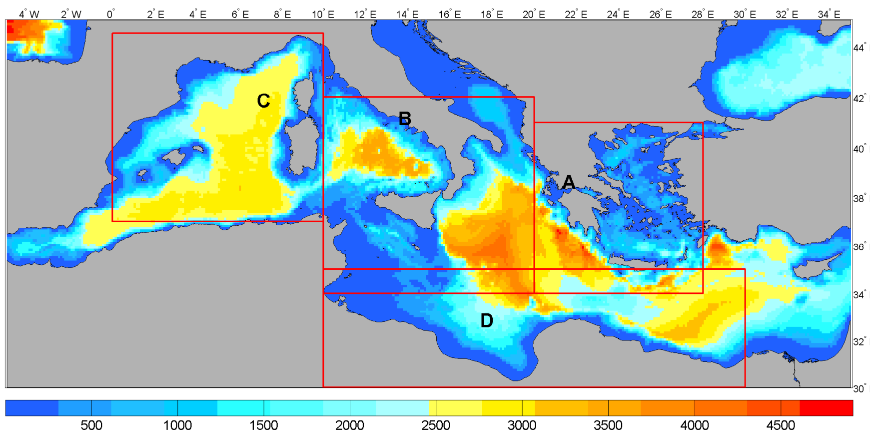
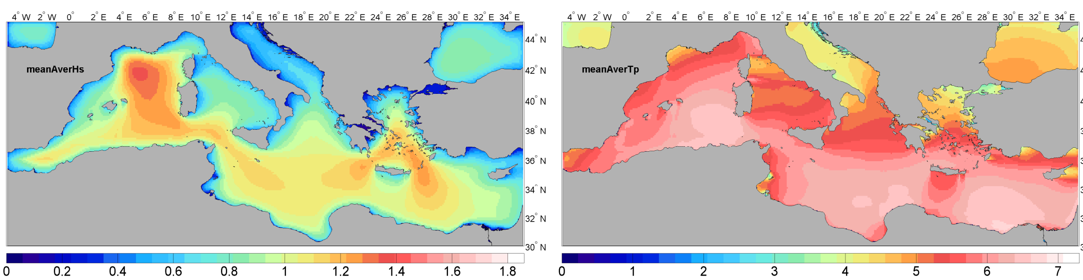


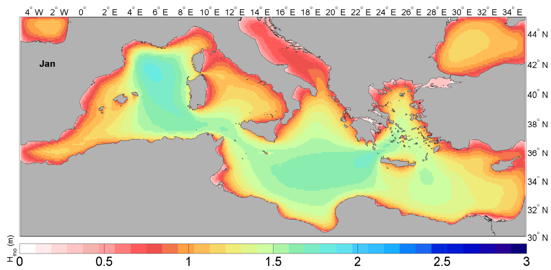
FIG. 1: Domains and bathymetry in meters



(a) H_{m0} in meters

(b) T_{peak} in seconds

FIG. 2: Mean resource characteristics in the region



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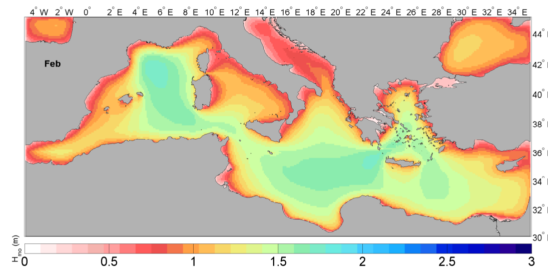

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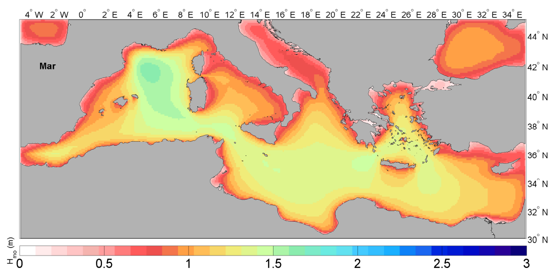
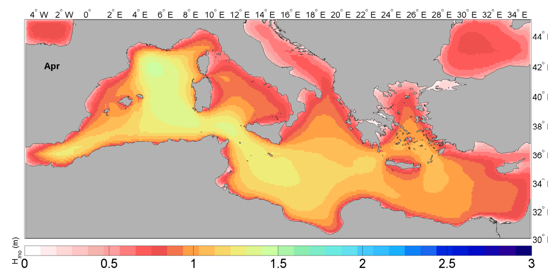
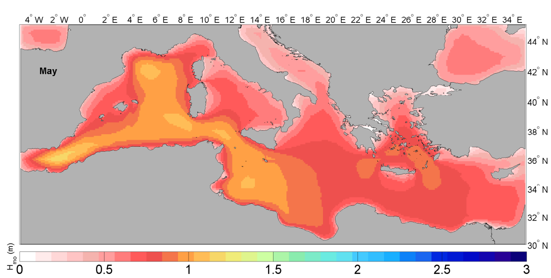


(c) March



(d) April

FIG. 3: Resource H_{m0} January-April



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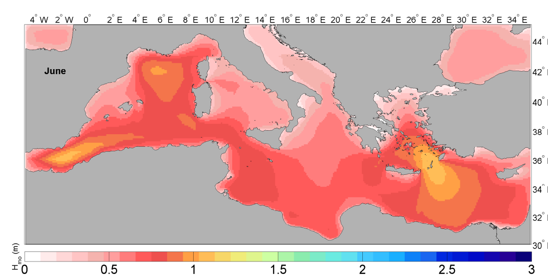
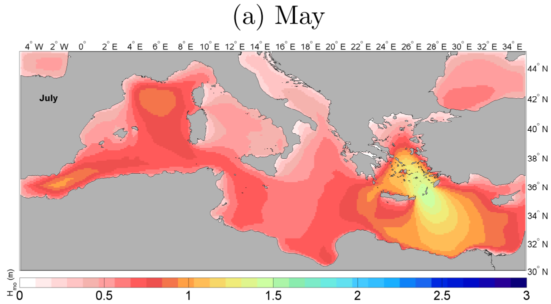
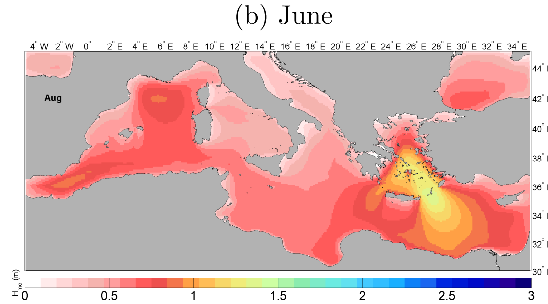


(b) June

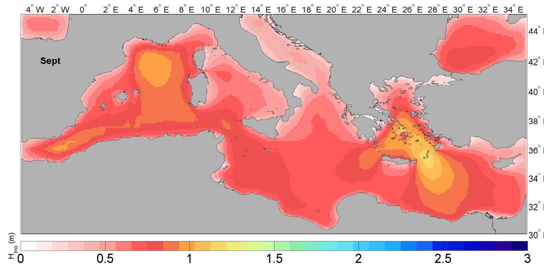


(c) July

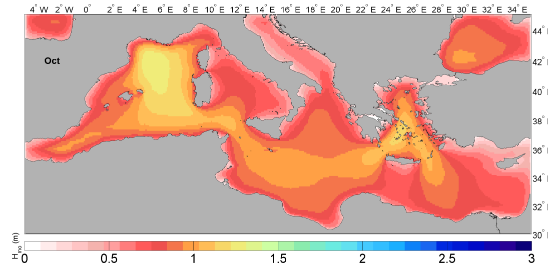


(d) August

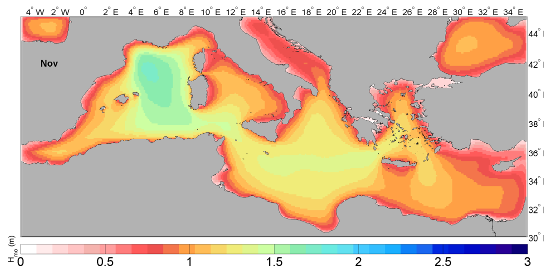
FIG. 4: Resource H_{m0} May-August



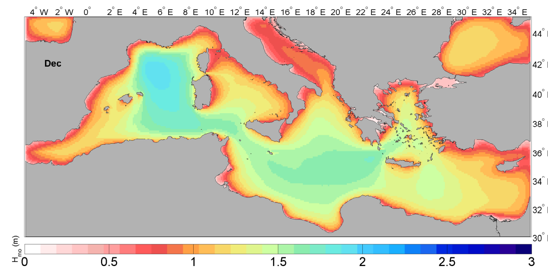
(a) September



(b) October

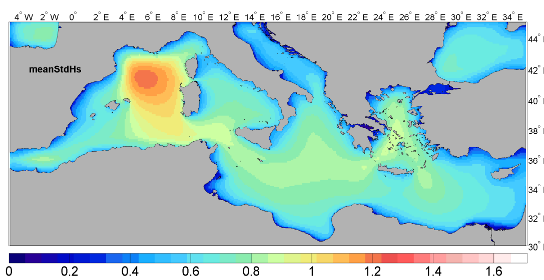


(c) November

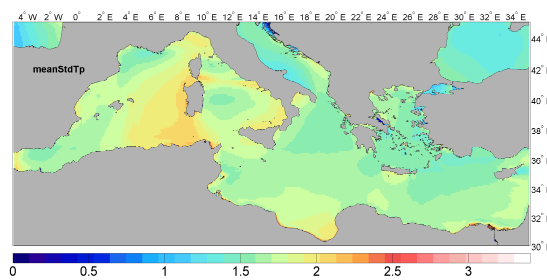


(d) December

FIG. 5: Resource H_{m0} September-December

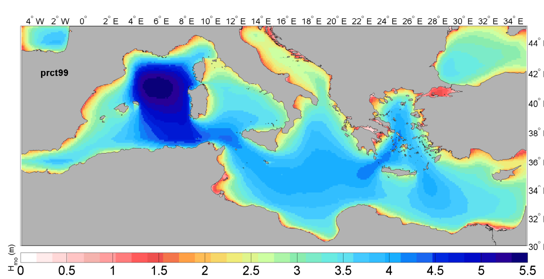


(a) H_{m0} in meters

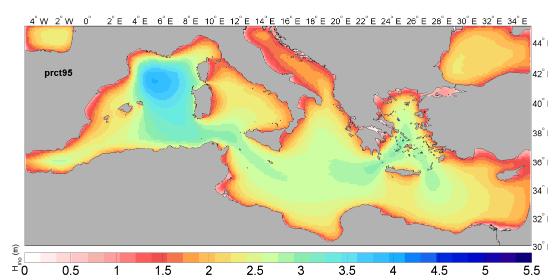


(b) T_{peak} in seconds

FIG. 6: Standard deviation (STD) ranges

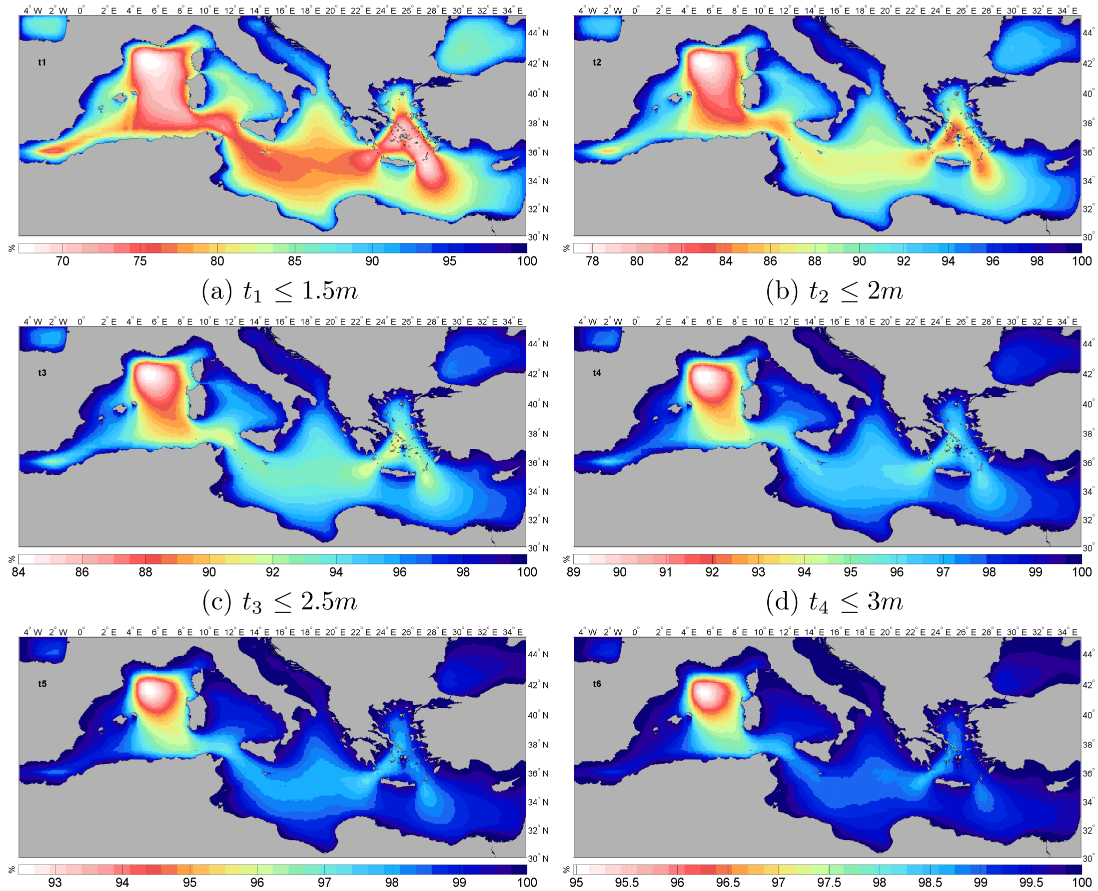


(a) 99^{th}



(b) 95^{th}

FIG. 7: H_{m0} highest percentiles



(a) $t_1 \leq 1.5m$ (b) $t_2 \leq 2m$

(c) $t_3 \leq 2.5m$ (d) $t_4 \leq 3m$

(e) $t_5 \leq 3.5m$ (f) $t_6 \leq 4m$

FIG. 8: H_{m0} Accessibility (%) of time based on (t)

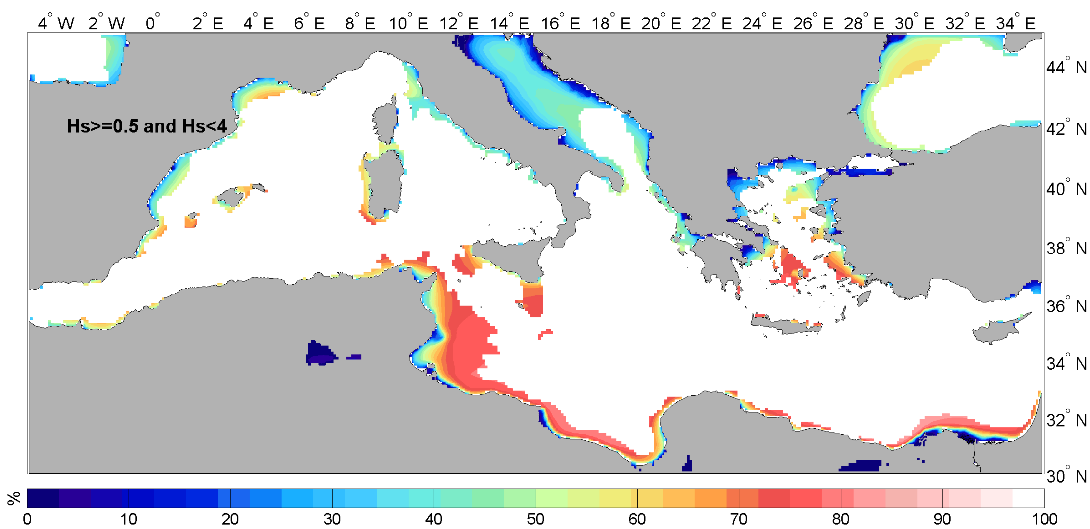
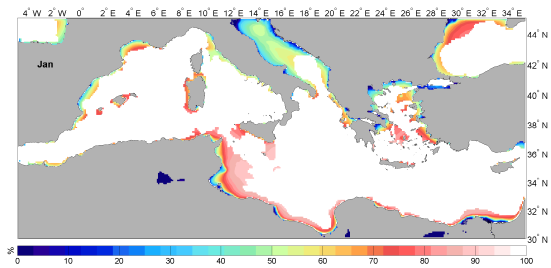
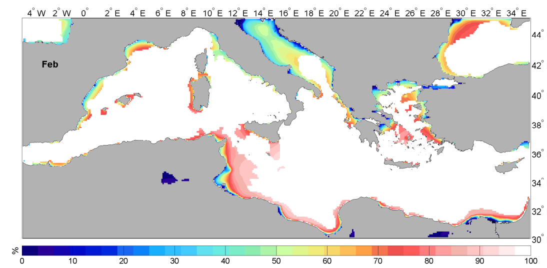


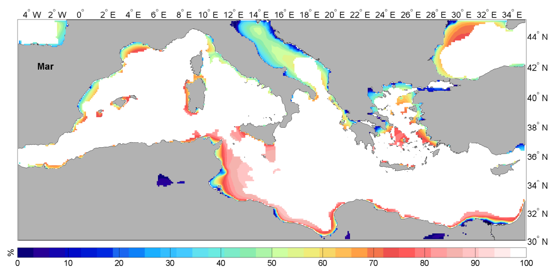
FIG. 9: Availability based on 0.5 m $\leq H_{m0} \leq$ 4 m for depths $\leq$ 250 m



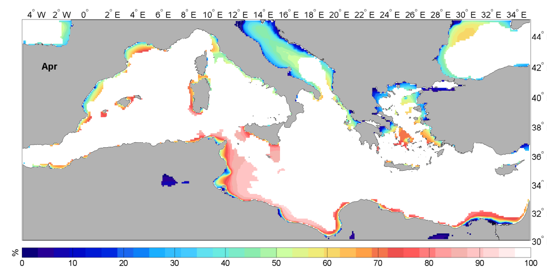
(a) January



(b) February

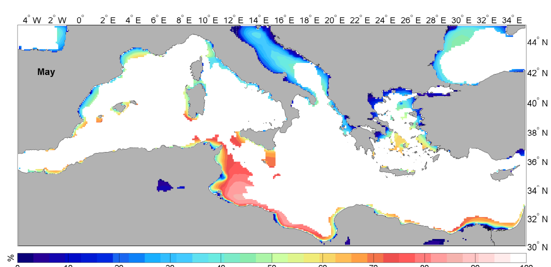


(c) March

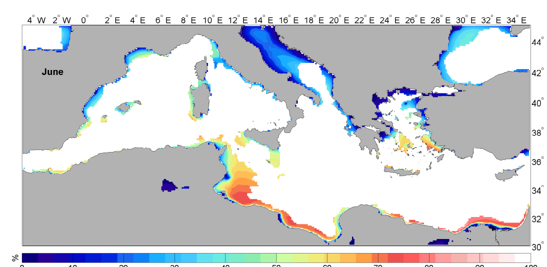


(d) April

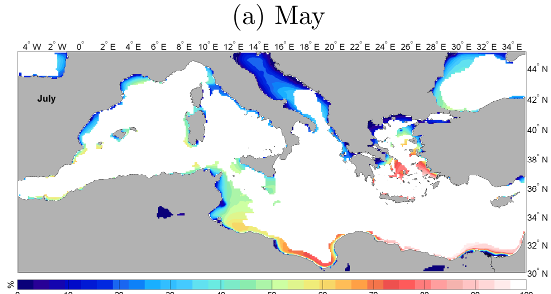
FIG. 10: Availability (%) based on H_{m0} January-April for depths $\leq$ 250 m



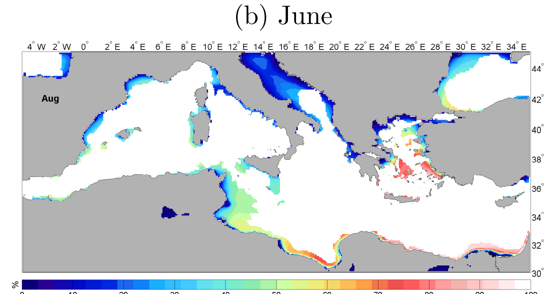
(a) May



(b) June

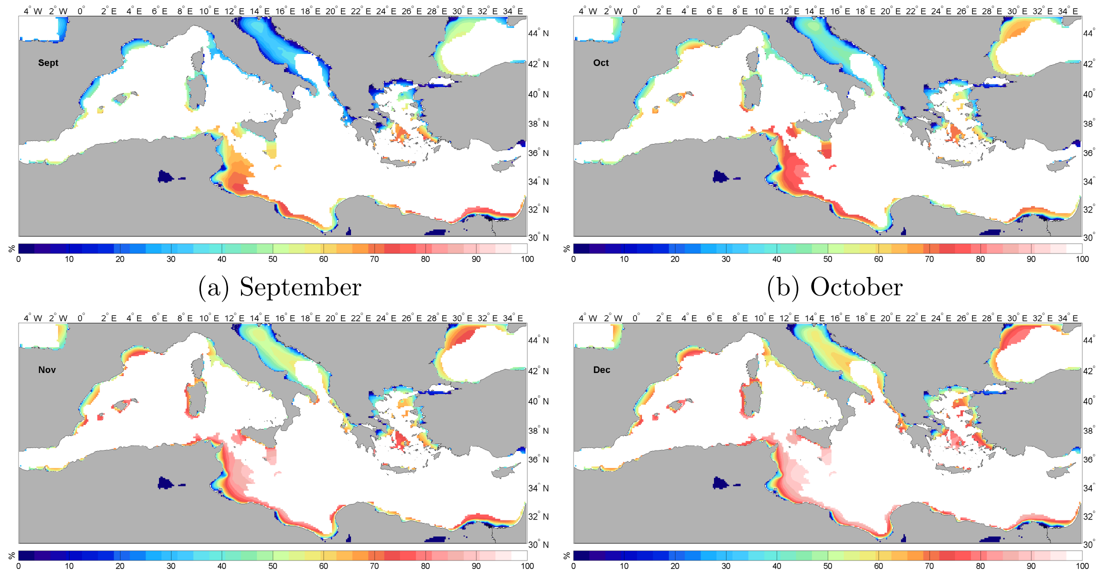


(c) July



(d) August

FIG. 11: Availability (%) based on H_{m0} May-August for depths $\leq$ 250 m



(a) September (b) October

(c) November (d) December

FIG. 12: Availability (%) based on H_{m0} for depths $\leq$ 250 m September-December

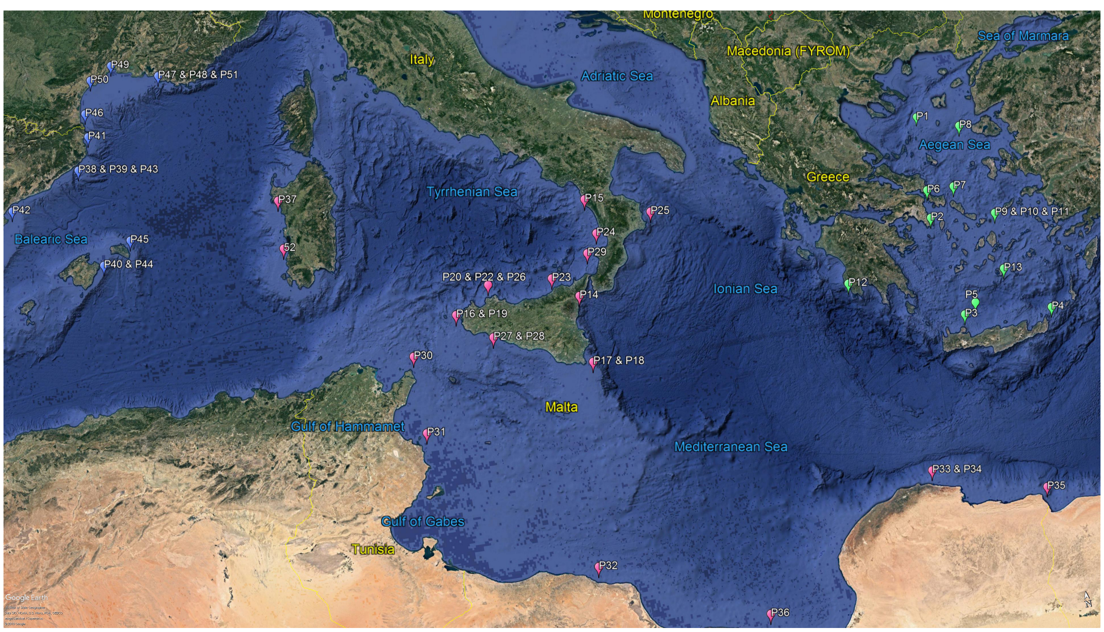
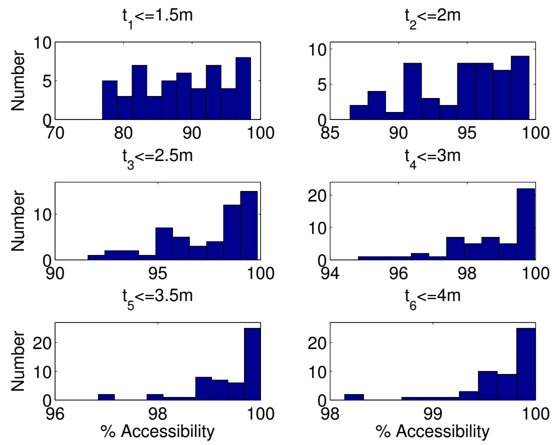
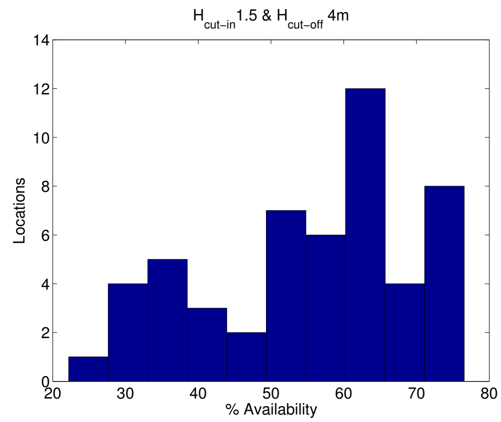


FIG. 13: Distribution of locations

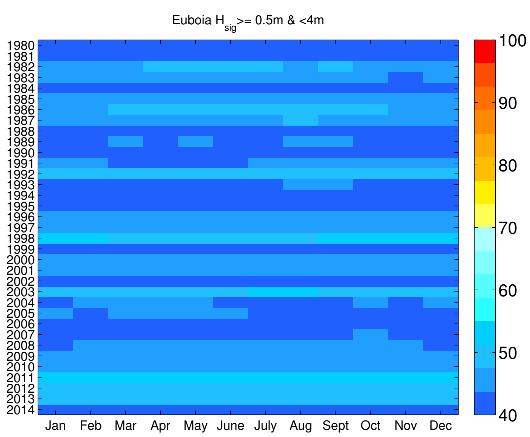


(a) Accessibility (%) for thresholds

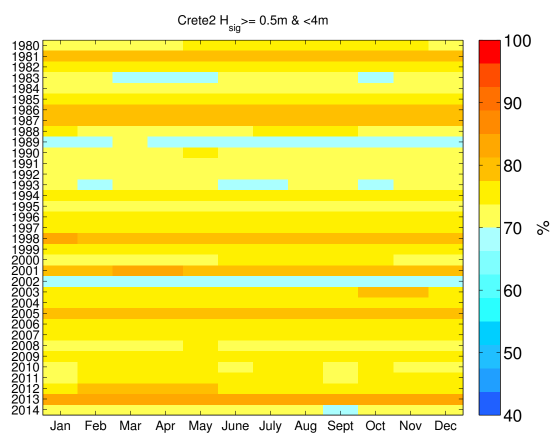


(b) Histogram Availability

FIG. 14: Accessibility and Availability distribution histograms of all locations



(a) Euboia



(b) Crete 2

FIG. 15: Availability (%) for $H_{cut-in/off}$

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TABLE 1: Implementation of Mediterranean Models

	Study	Model	Period (years)	Spatial Resolution	Parameters
Mediterranean	(Medatlas Group 2004)	WAM	10	$0.5^o x 0.5^o$ & $0.25^o x 0.25^o$	Waves, Wave Climate
Mediterranean	(Ratsimandresy et al. 2008)	WAM	44	$0.5^o x 0.5^o$	Waves, Wave Power
Mediterranean	(Liberti et al. 2013)	WAM	10	$0.625^o x 0.625^o$	Wave Power
Mediterranean	(Besio et al. 2016)	WW3	35	$0.12^o x 0.09^o$	Wave Power
Mediterranean	(Lavidas et al. 2016)	SWAN	35	$0.1^o x 0.1^o$	Waves, Wave Power

TABLE 2: Description of Locations

Location	$\overline{H_{m0}}$	$\overline{H_{max}}$	$\overline{H_{STD}}$	$\overline{H_{95^{th}}}$	$\overline{H_{99^{th}}}$	$\overline{t_1}$	$\overline{t_2}$	$\overline{t_3}$	$\overline{t_4}$	$\overline{t_5}$	$\overline{t_6}$	$\overline{Avail}$	$\overline{P_{wave}}$
	$meters$					Accessibility (%)						(%)	kW/m
Athos (P1)	0.81	6.82	0.79	2.44	3.67	84.45	91.36	95.34	97.57	98.74	99.34	52.06	3.89
Attika (P2)	0.62	5.60	0.52	1.66	2.34	92.92	97.78	99.33	99.81	99.93	99.97	47.37	1.71
Crete1 (P3)	0.80	6.26	0.64	2.07	3.22	88.49	94.47	97.37	98.64	99.33	99.72	60.42	3.54
Crete2 (P4)	1.05	6.65	0.75	2.48	3.64	78.36	89.85	95.13	97.61	98.81	99.38	74.86	5.28
E1mea (P5)	0.72	6.20	0.61	1.91	3.09	90.61	95.57	97.87	98.83	99.45	99.74	53.07	2.87
Euboia (P6)	0.67	6.55	0.68	2.04	3.27	89.71	94.74	97.38	98.60	99.23	99.56	44.78	2.96
Kythnos (P7)	0.86	6.26	0.73	2.30	3.27	83.02	92.01	96.38	98.43	99.31	99.72	58.26	3.68
Lesvos (P8)	0.89	6.99	0.77	2.46	3.63	83.13	90.89	95.26	97.59	98.79	99.45	61.17	4.06
Mykonos (P9)	0.88	5.18	0.61	2.00	2.63	83.59	95.06	98.58	99.64	99.93	99.98	65.39	2.87
Naxos (P10)	0.79	4.21	0.60	1.94	2.58	86.43	95.71	98.79	99.66	99.94	100.00	59.68	2.44
Paros (P11)	0.86	4.50	0.63	2.05	2.73	83.51	94.35	98.30	99.46	99.85	99.99	62.95	2.89
Pylos (P12)	0.94	7.79	0.73	2.43	3.53	82.86	91.09	95.48	97.78	98.94	99.48	66.53	4.74
Santorini (P13)	1.01	5.84	0.71	2.40	3.38	80.13	90.67	95.73	98.05	99.19	99.64	73.25	4.64
Catania (P14)	0.37	4.66	0.39	1.12	1.96	97.73	99.07	99.63	99.83	99.93	99.97	22.19	1.02
Cetraro (P15)	0.60	7.49	0.56	1.72	2.83	93.15	96.73	98.41	99.22	99.63	99.81	41.85	2.50
Desil (P16)	1.08	7.65	0.86	2.80	4.13	76.90	87.10	92.83	96.08	97.85	98.83	71.02	6.86
GasilA (P17)	0.95	6.20	0.71	2.34	3.43	81.92	91.47	96.05	98.03	99.10	99.58	68.06	4.95
GasilB (P18)	1.05	6.86	0.78	2.58	3.74	77.96	88.70	94.41	97.21	98.59	99.32	72.96	6.06
Italy1 (P19)	0.84	6.22	0.67	2.19	3.20	85.63	93.27	96.94	98.62	99.39	99.76	61.25	4.10
Italy2 (P20)	0.80	6.54	0.72	2.27	3.46	86.53	92.92	96.33	98.09	99.06	99.54	55.95	4.13
Italy3 (P21)	0.68	4.97	0.51	1.69	2.49	92.60	97.29	99.03	99.70	99.91	99.97	52.77	2.50
Italy4 (P22)	0.81	5.62	0.58	1.95	2.81	88.45	95.41	98.26	99.29	99.71	99.90	63.14	3.26
Italy5 (P23)	0.50	6.51	0.50	1.51	2.52	94.95	97.76	98.97	99.53	99.77	99.90	32.67	1.78
Italy6 (P24)	0.59	8.15	0.57	1.72	2.87	93.08	96.65	98.32	99.16	99.58	99.78	41.11	2.55
Italy7 (P25)	0.62	6.83	0.56	1.73	2.66	92.51	96.86	98.65	99.45	99.76	99.88	43.77	2.24
Mazzaro (P26)	0.93	6.74	0.75	2.43	3.58	82.10	90.94	95.45	97.75	98.89	99.46	64.67	5.12
Palermo (P27)	0.93	6.74	0.75	2.43	3.58	82.10	90.94	95.45	97.75	98.89	99.46	64.67	5.12
Ronmaz (P28)	0.93	6.74	0.75	2.43	3.58	82.10	90.94	95.45	97.75	98.89	99.46	64.67	5.12
Tauro (P29)	0.51	7.74	0.53	1.54	2.70	94.64	97.42	98.70	99.34	99.68	99.84	33.87	1.97
Tynisia1 (P30)	1.04	7.25	0.81	2.67	3.89	78.59	88.53	93.84	96.70	98.31	99.15	71.42	6.16
Tynisia2 (P31)	0.63	4.14	0.42	1.47	2.14	95.38	98.59	99.61	99.90	99.98	100.00	51.34	1.69
Libya1 (P32)	0.87	6.95	0.58	1.99	3.06	88.51	95.07	97.66	98.90	99.51	99.77	72.91	3.94
Libya2 (P33)	0.89	7.34	0.65	2.20	3.36	86.99	93.50	96.64	98.29	99.18	99.59	70.84	4.58
Libya3 (P34)	0.86	5.53	0.49	1.79	2.60	90.71	96.80	98.78	99.55	99.81	99.94	76.56	3.24
Libya4 (P35)	0.86	5.53	0.49	1.79	2.60	90.71	96.80	98.78	99.55	99.81	99.94	76.56	3.24
Libya5 (P36)	0.84	5.32	0.49	1.79	2.67	91.12	96.60	98.66	99.46	99.79	99.91	76.25	3.38
Alghero (P37)	1.02	7.83	0.97	3.04	4.57	78.20	86.44	91.59	94.82	96.84	98.14	59.53	8.03
Barca1 (P38)	0.50	3.85	0.38	1.26	1.96	97.14	99.09	99.72	99.93	99.99	100.00	34.46	1.27
Barca2 (P39)	0.50	3.77	0.37	1.24	1.93	97.29	99.17	99.76	99.95	100.00	100.00	34.86	1.24
Capder (P40)	0.81	6.16	0.62	2.03	3.09	88.30	94.70	97.54	98.84	99.47	99.79	62.33	3.76
Palamos (P41)	0.63	5.16	0.48	1.58	2.38	94.13	97.92	99.23	99.71	99.89	99.96	49.38	2.09
Spain1 (P42)	0.46	3.60	0.31	1.05	1.68	98.56	99.52	99.85	99.97	100.00	100.00	31.21	0.93
Spain2 (P43)	0.48	5.10	0.39	1.24	2.00	97.08	99.00	99.61	99.87	99.94	99.97	32.40	1.28
Spain3 (P44)	0.86	7.21	0.71	2.28	3.50	85.70	92.79	96.26	98.07	99.00	99.50	61.86	4.50
Spain4 (P45)	1.01	8.05	0.91	2.91	4.49	79.92	88.10	92.68	95.38	97.13	98.27	64.41	7.13
Fr61191 (P46)	0.49	6.08	0.43	1.26	2.19	97.00	98.69	99.36	99.70	99.87	99.95	35.21	1.21
Fr61284 (P47)	0.65	5.50	0.49	1.56	2.35	94.28	98.07	99.25	99.71	99.89	99.96	51.78	1.81
Fr61289 (P48)	0.74	5.25	0.56	1.83	2.49	89.33	96.64	99.04	99.73	99.91	99.96	57.01	2.43
Fr6190 (P49)	0.47	5.57	0.43	1.26	2.24	96.58	98.54	99.34	99.72	99.89	99.96	31.62	1.16
France1 (P520)	0.47	5.63	0.42	1.23	2.19	96.90	98.67	99.39	99.73	99.89	99.95	33.44	1.17
France2 (P51)	0.67	5.77	0.51	1.63	2.44	93.30	97.76	99.11	99.64	99.86	99.94	52.90	1.95
ItalyAl (P52)	0.91	7.19	0.87	2.70	4.03	80.84	88.77	93.61	96.49	98.08	98.96	56.77	6.56